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16. ABSTRACT The activated sludge process is a common and useful method for treating wastewater. However, because of the necessity for aerating the sludge, the potential exists for release of a variety of viable and nonviable pollutants to the ambient atmosphere. This paper reports the results of an 8-month monitoring study in the vicinity of a large activated sludge plant in a Chicago suburb. Based on the measurements of this study, the wastewater treatment plant is a significant source of TVP (total viable particles) and total coliforms. Atmospheric TVP concentrations were elevated above background out to 1.6 km. Levels for total coliforms were reduced to background at less than 0.8 km, probably reflecting the limited viability of these bacteria in air. On the average, 95% of the viable particles discharged from the plant were greater than 2.1 um, and 99% of the total coliform particles were greater than 1.1 um. The health implications of these pollutants for populations living in the vicinity of the plant are not well defined. But the fact that plant emissions have the potential for relatively widespread dispersion should alert those concerned with the operation, planning, and design of activated sludge processes to incorporate the most effective control measures possible.

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Characterization of air pollutants from an activated sludge process

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Journal Article

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The activated sludge process is a common and useful method for treating wastewater. However, because of the necessity for aerating the sludge, the potential exists for release of a variety of viable and nonviable pollutants to the ambient atmosphere. These pollutants may subsequently harm the health of exposed populations. A number of studies have investigated airborne discharges from activated sludge processes[1-8] and trickling filters,[5,6,9,10] but most reported only a limited number of samples and none was carried out over an extended period of time. This paper reports the results of an 8-month monitoring study in the vicinity of a large activated sludge plant in a Chicago suburb.[11]

The plant is located in a residential area that also includes some light industry. Wastewater treatment includes primary separation, an activated sludge process with diffused aeration, and final effluent chlorination. There are no facilities for sludge digestion, and wasted sludge is pumped through a tunnel to another plant for processing. The surface area of the aeration tanks is about 55 000 m^2. During the study period (April through November 1977), the plant had a median flow rate of 1.11×10^9 l/d (292 mgd) and a median air rate of 4.62×10^6 m^3/d (163×10^6 cu ft/day). Figure 1 is a map of the plant and study area. A wind rose, based on on-plant measurements, is given in Figure 2.

Activated sludge plant emissions of airborne viable bacteria have the potential for relatively widespread dispersion.

Measurements of air pollutants were taken on a regular basis at the plant and in the surrounding area out to 1.6 km. The air pollutants included total aerobic-bacteria-containing particles, hereafter referred to as total viable particles (TVP), total suspended particulate (TSP), NO_2, SO_2, Cl_2, NH_3, and H_2S. Particulate filters were also analyzed for nitrates (NO_3^-) and sulfates ($SO_4^=$), As, Cd, Cr, Cu, Hg, Mn, Ni, Pb, Sb, Se, Sn, and V. Total coliform were collected and analyzed over the final 2.5 months of the project. Grab samples of wastewater entering the aeration tanks, taken concurrently with the air samples, were analyzed for the same pollutants.

EXPERIMENTAL

The sampling methodology was structured to characterize study area concentrations as completely as possible within equipment and manpower limitations. Total viable particles were collected with 6-stage cascade impactors (Anderson 2000) that operated at an air flow rate of 0.03 m^3/min (1 cu ft/min) for 15 minutes. The samplers were situated 1.8 m above the ground and were located away from tall buildings or other obstructions. The collection media was BBL triplicase soy agar (TSA) with the mold inhibitor actidone. The sterilized media-filled collection plates were refrigerated until samples were collected and were then incubated for 48 ± 5 hours at 35°C.[11] A Quebec colony counter was used to determine particle numbers. Before a sampling run, the wind direction was determined from an on-plant weather station, and, over the next 2 hours, three samples were collected downwind (at the plant site, 0.8 km, and 1.6 km) and one sample was taken 0.8 km upwind. The samples were taken sequentially over this time period, but the order in which the sites were monitored was chosen randomly. The sample locations are indicated in Figure 1. Sampling runs were carried out at five separate intervals during every 2-week period, daytime and evening samples being collected with about equal frequency. Total coliform bacteria were initially sampled using Porton impingers[1] operating for 15 minutes at a flow rate of 12.5 l/min, with phosphate-buffered water containing 0.25% sodium alginate as the collecting media. However, environmental concentrations were less than the detectable limit of this method, and for the final 2.5 months of the project (September through November), total coliforms were collected for 30 minutes with the Andersen sampler using M-Endo broth containing 1.5% Bacto-Agar as media and were incubated at 35°C for 24 hours.[11] Counting was carried out under fluorescent light with a binocular microscope,

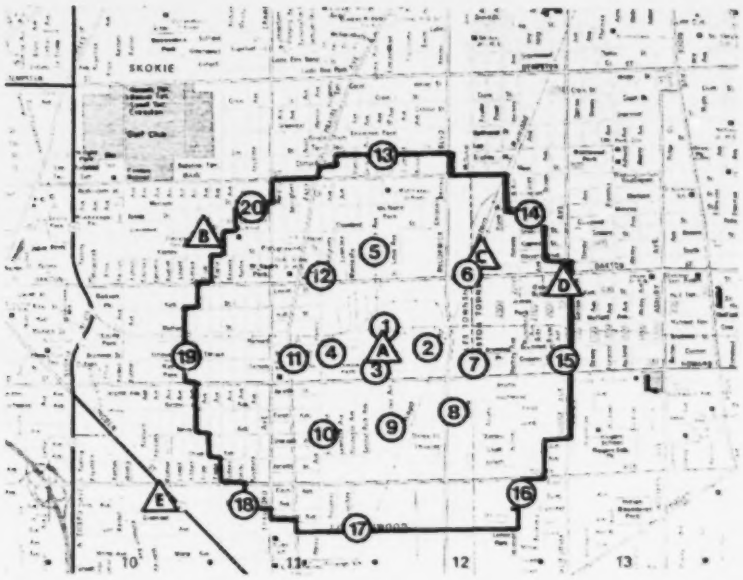

Figure 1—Sampling locations and study area.

and the sampling methodology was the same as that used for TVP. Counting procedures for both pollutants incorporated the positive hole count correction factor.[12] The samplers' flow rates were calibrated with a wet test meter at the beginning of the project and at three other times during the study and were found to remain essentially constant.

Nonviable pollutants such as TSP and the gases were collected on a 24-hour basis. Sampling locations, given in Figure 1, were chosen to characterize the areas where there was the greatest population concentration; to correspond to a preliminary evaluation of prevailing wind direction; and for convenience and protection from vandalism. Total suspended particulates were collected using high-volume samplers, and filters were weighed and conditioned using the U. S. Environmental Protection Agency (EPA) method.[13] A calibration assembly was used to make calibrations periodically during the study. Gases were measured with bubblers (average flow rate for each bubbler was 200 mg/min) with a modified manifold and bubbler to collect NH_3 (flow rate of 5 l/min). The critical flow orifices that controlled flow rates were calibrated every third run. High-volume samplers were operated at all five sites every fifth day, with two being operated at the plant location. Glass fiber filters were used for TSP measurement. Whatman 541 filters were used for trace element analysis. The sampling schedule was staggered with the plant and sites B and E monitored for metals 1 day while TSP, $SO_4^=$, and NO_3^- were measured at the plant and sites C and D. The next sampling day the procedures were reversed. Some size-differentiated TSP measurements were also made at the plant site using a 5-stage Andersen high-volume attachment. Bubbler samples were collected at three locations every fifth day using the same sampling scheme as for trace elements. Trace element analysis was carried out using energy dispersive x-ray fluorescence spectrometry.[14] Various wet chemical analyses were used for $SO_4^=$,[15] NO_3^-,[16] H_2S,[17] NH_3,[18] Cl_2,[19] SO_2,[20] and NO_2.[21]

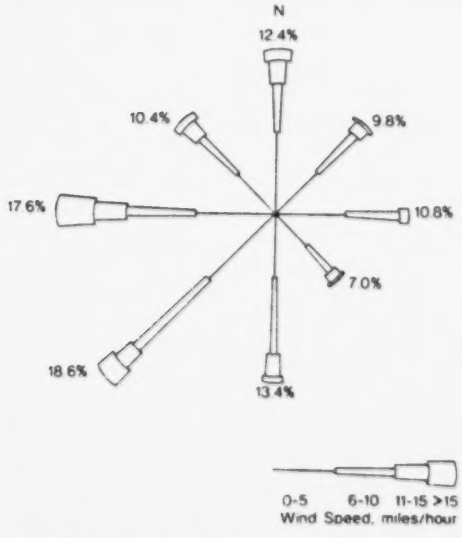

Figure 2—Wind rose based on on-plant measurements.

Grab samples of wastewater were analyzed for total viable bacteria, total coliform, fecal coliform, trace elements, sulfates, and nitrates. The spread plate procedure with TSA was used for total viable bacteria, with appropriate dilutions of each sample being applied to

duplicate plates.[11] Total coliform were determined using the standard membrane filter procedure[18] and M-Endo media. Incubation times and temperatures were the same as with air samples. Fecal coliforms were determined with the standard membrane filter technique on M-FC media with incubation at 44.5°C in a water bath in water-tight containers for 24 ± 2 hours. An attempt was made to collect fecal coliforms in air using impingers, but, as with total coliform, the environmental concentrations were less than the procedure's detectable limit. Not enough Andersen samplers were available to the project to monitor further for fecal coliform. Details of sample preparation for trace elements, $SO_4^=$, and NO_3^- analyses were given elsewhere.[11] Analyses procedures were the same as those for these materials in the air.

Continuous measurements of wind speed and direction (at 10 m), ultraviolet and solar radiation, temperature, and relative humidity were collected at the plant site. On the few occasions when the meteorological monitoring station was inoperable, data were used from Midway Airport (about 26 km away). The use of Midway data was not considered to be a problem as the number of hours replaced was less than 20% of the study period, and reasonable correlations were found between the two data sets over the whole study (for example, $r = 0.95$ for hourly temperature values).

Table 1—Study period average total viable and coliform concentrations by sampling site and wind direction.

		Particles/m³			
		Downwind Concentrations		Upwind Concentrations	
Sampling Site	Distance from Plant (km)	Total Viable	Coliforms	Total Viable	Coliforms
1	—	447 (12)*	3.96 (7)		
2	—	381 (21)	3.42 (12)		
3	—	347 (21)	17.08 (5)		
4	—	354 (13)	12.20 (2)		
5	0.8	268 (6)	1.10 (6)	59 (7)	0.37 (3)
6	0.8	191 (8)	2.60 (3)	157 (10)	
7	0.8	155 (14)	1.20 (9)	135 (12)	0.00 (2)
8	0.8	199 (7)	1.10 (2)	378 (3)	
9	0.8	294 (7)	0.37 (3)	227 (5)	0.94 (7)
10	0.8	93 (9)		161 (6)	0.37 (3)
11	0.8	228 (13)	0.00 (12)	118 (16)	1.97 (9)
12	0.8	232 (4)		54 (3)	1.65 (2)
13	1.6	169 (6)	2.03 (6)		
14	1.6	580 (9)	0.73 (3)		
15	1.6	200 (10)	1.10 (8)		
16	1.6	60 (6)	0.00 (2)		
17	1.6	174 (6)	0.00 (3)		
18	1.6	248 (8)			
19	1.6	171 (12)	0.55 (2)		
20	1.6	144 (3)			

* Number of samples indicated in parentheses.

Table 2—Median size distributions for total viable particles and total coliforms based on all samples.

		Total Viable Particles		Total Coliform	
Stage	Diameter (μm)	(TVP/m³)	(%)	(Coliforms/m³)	(%)
1	>7	103	43	1.28	50
2	4.7–7	54	23	0.65	25
3	3.3–4.7	43	18	0.40	16
4	2.1–3.3	18	8	0.13	5
5	1.1—2.1	13	6	0.08	3
6	0.65–1.1	5	2	0.02	1
TOTAL		236	100	2.56	100

RESULTS

The mean concentrations of TVP and total coliform by site are given in Table 1 and the median size distributions based on all measurements are given in Table 2. Figures 3 and 4 are maps of the average upwind (background) and downwind concentrations. The values between monitoring points were interpolated using a weighting algorithm based on the inverse square of the distance between receptor point and monitoring site.[22] The mean wastewater concentrations were 1.69×10^6 bacteria/100 ml for TVP, 5.35×10^7 total coliform/100 ml, and 7.74×10^6 fecal coliform/100 ml.

The mean concentrations of each of the nonviable pollutants are given by site in Table 3. The mean size distribution for TSP at the plant site is given in Table 4. Wastewater concentrations of trace elements, NO_3^-, and $SO_4^=$ are shown in Table 5.

ANALYSIS

Viable pollutants. Figure 3 indicates that the plant is a source of TVP. The isopleth pattern also shows that there is another source of TVP northeast of the plant near Sampling Site 14. This source influences the downwind measurements made at Site 14 and the upwind measurements made at Site 6, halfway between the plant and Site 14 (Table 1). The ultimate purpose of the measurement program was to characterize environmental exposures over the whole study period. Consequently, mean concentrations over the study period were demonstrated for the plant (downwind of the aeration tanks), 0.8 km upwind and 0.8 and 1.6 km downwind of the plant. These averages were based on all measurements from all wind directions. The averages, with and without Site 6 (upwind) and Site 14 (downwind), are given in Table 6. Both sets of data show a decrease in concentration with distance from the plant, and downwind averages at all sites are higher than the upwind averages. If the data from Sites 14 (downwind) and 6 (upwind) are not included in the averages, both the upwind concentration and that at 1.6 km are de-

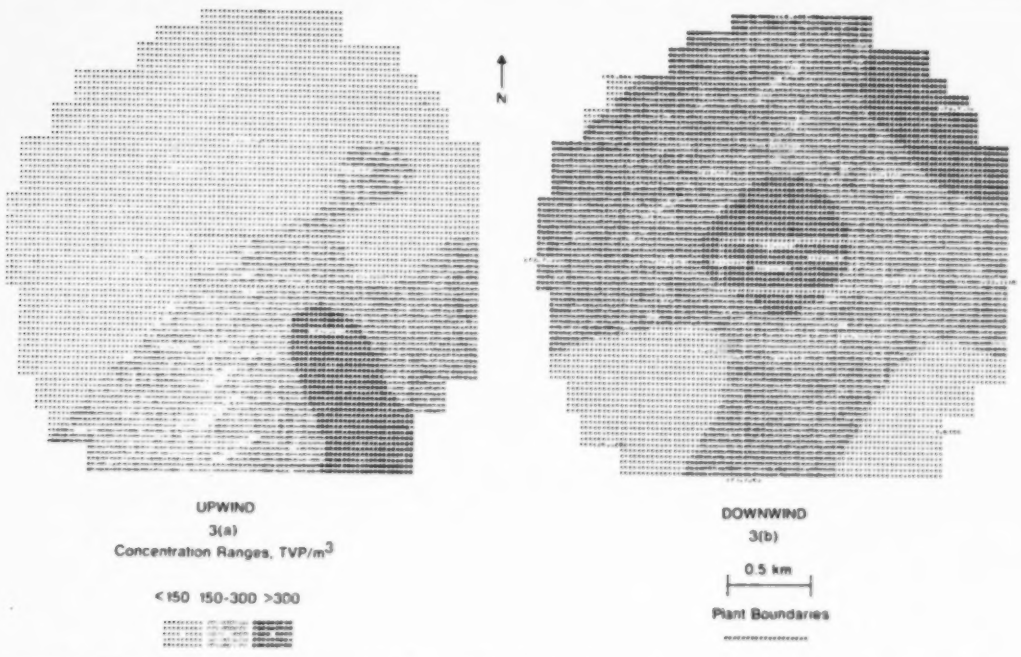

Figure 3—Upwind and downwind concentration profiles for total viable particles: 3(a) upwind; 3(b) downwind.

creased (Table 6). When all sites are included, t-tests comparing the mean concentrations upwind with those for each of the downwind distances indicate that all are significantly higher than background ($p < 0.05$). If Site 6 (upwind) and Site 14 (downwind) are not included, the plant and 0.8-km downwind concentrations are significantly higher than the upwind level ($p < 0.05$), but the 1.6-km site is not. Comparison of mean values for

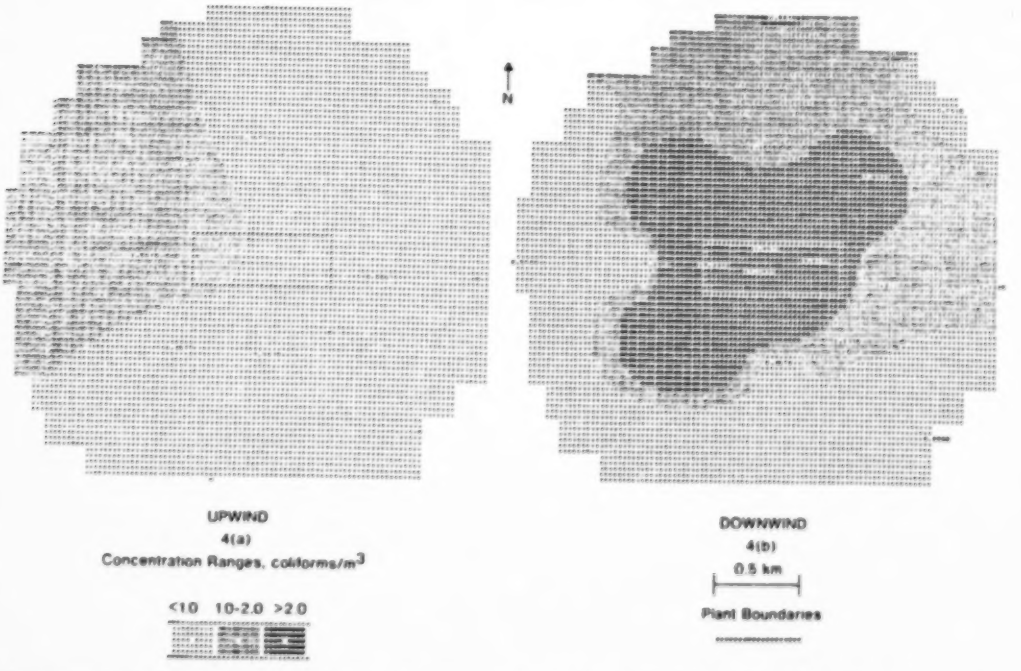

Figure 4—Upwind and downwind concentration profiles for total coliforms: 4(a) upwind; 4(b) downwind.

Table 3—Mean concentrations of nonviable pollutants by site.

Pollutant	Detection Limit (μg/m³)	Site (μg/m³) A		B		C		D		E	
Particulates											
TSP	1.00	77.56	(45/45)*	74.47	(30/30)	87.45	(22/22)	82.21	(23/23)	68.13	(20/20)
NO_3	0.01	1.60	(40/40)	1.40	(27/27)	1.46	(21/21)	1.57	(21/21)	1.44	(18/18)
$SO_4^=$	0.01	14.08	(28/28)	11.31	(27/27)	13.43	(21/21)	13.03	(21/21)	12.04	(18/18)
As	0.011	0.001 2	(2/32)	0.000 0	(0/13)	0.000 7	(1/15)	0.001 9	(2/16)	0.000 0	(0/16)
Cd	0.009	0.004 2	(7/32)	0.000 0	(0/13)	0.001 8	(2/15)	0.003 3	(3/16)	0.006 9	(5/16)
Cr	0.022	0.000 0	(0/32)	0.000 0	(0/13)	0.005 8	(2/15)	0.000 0	(0/16)	0.011 8	(1/16)
Cu	0.009	0.214 1	(31/32)	0.369 1	(13/13)	0.424 7	(15/15)	0.397 1	(16/16)	0.312 3	(16/16)
Hg	0.009	0.001 5	(4/32)	0.002 1	(3/13)	0.001 3	(1/15)	0.002 6	(2/16)	0.000 0	(0/16)
Mn	0.022	0.029 2	(19/32)	0.018 3	(4/13)	0.038 0	(10/15)	0.037 6	(11/16)	0.026 2	(10/16)
Ni	0.009	0.000 3	(1/32)	0.000 0	(0/13)	0.000 6	(1/15)	0.000 6	(1/16)	0.000 0	(0/16)
Pb	0.018	0.608 3	(32/32)	0.741 2	(13/13)	0.840 0	(15/15)	0.645 5	(16/16)	0.839 4	(16/16)
Sb	0.011	0.001 8	(5/32)	0.003 2	(2/13)	0.000 0	(0/15)	0.001 8	(2/16)	0.002 4	(2/16)
Se	0.007	0.002 5	(6/32)	0.002 9	(3/13)	0.001 7	(2/15)	0.002 1	(4/16)	0.004 1	(6/16)
Sn	0.011	0.003 7	(9/32)	0.002 1	(2/13)	0.002 2	(2/15)	0.002 2	(2/16)	0.002 2	(3/16)
V	0.002	0.002 1	(16/32)	0.001 4	(4/13)	0.001 9	(8/15)	0.001 7	(8/16)	0.004 7	(6/16)
Gases											
Cl_2	2.12	11.05	(30/31)	11.80	(13/14)	11.03	(14/14)	13.59	(13/13)	11.42	(13/14)
H_2S	0.70	0.11	(1/25)	0.00	(0/11)	0.22	(1/12)	0.27	(1/11)	0.00	(0/12)
NH_3	2.29	0.36	(3/13)	0.43	(2/5)	0.17	(1/7)	0.57	(3/7)	0.25	(1/7)
NO_2	7.60	42.72	(34/35)	47.32	(15/16)	57.01	(16/16)	54.85	(16/16)	53.49	(17/18)
SO_2	3.30	3.27	(11/36)	7.22	(10/17)	7.08	(9/17)	8.76	(10/16)	3.11	(7/16)

* (Number of samples above detection limit/total samples). Averages are based on all samples with those below the detectable limit assigned zero concentration.

each distance for summer and fall (which began September 21) did not show any significant seasonal differences.

The coliform data of Figure 4 and Table 6 show a similar pattern, but without the complication of an additional source. The plant concentration is significantly greater than the upwind concentration ($p < 0.05$), but the other downwind concentrations are not.

An analysis of the TVP size distributions for the plant, upwind, and downwind sites indicated no significant differences by distance. However, the mean plant and 0.8-km downwind concentrations of particles greater than 2.1 μm (Stages 1–4) were significantly higher ($p < 0.05$) than the 0.8-km upwind mean in this size range. No significant differences were found for particles less than 2.1 μm. The pattern for total coliform distributions is similar except that significant differences in mean plant concentrations existed through Stage 5 (greater than 1.1 μm) when upwind and downwind observations were compared.

Table 4—Mean total suspended particulate size distribution (plant site).

Stage	Diameter (μm)	TSP Concentration* (μg/m³)	TSP Weight (%)
1	>7.0	21.0	28.7
2	3.3–7.0	15.0	20.6
3	2.0–3.3	9.8	13.4
4	1.1–2.0	10.7	14.8
5	0.01–1.1	16.3	22.5
Total		72.8	100.0

* Based on 17 samples.

Table 5—Mean concentrations of sulfate, nitrate, and trace elements in wastewater.

Element	Detection Limit (μg/l)	Number of Samples Total	Number of Samples Above Detection Limit	Mean Concentration (μg/l)
As	60	19	19	171
Cd	3	19	19	129
Cr*	—	—	—	—
Cu	2	19	19	218
Hg	4	19	0	0
Mn*	—	—	—	—
Ni	2	19	19	215
Pb	2	19	19	277
Sb	1	19	10	1.4
Se	2	19	0	0
Sn	1	19	19	60
V	12	12	0	0
$SO_4^=$	100	27	27	26 600
NO_3^-	100	27	27	7 600

* Do not precipitate in sample preparation procedure.

Table 6—Mean concentrations of total viable particles and total coliform by distance from the plant.

	Total Viable Particulates/m³					
	All Sites		Excluding Site 14 Downwind and Site 6 Upwind		Total Coliforms/m³	
Location	Mean Concentration	Standard Deviation	Mean Concentration	Standard Deviation	Mean Concentration	Standard Deviation
0.8 km upwind	143 (62)[a]	123	141 (52)	121	1.15 (26)	1.8
On-plant downwind	376[b] (68)	339	376[b] (68)	339	6.87[b] (26)	8.9
0.8 km downwind	198[b] (68)	155	198[b] (68)	155	1.15 (25)	2.0
1.6 km downwind	218[b] (60)	262	155 (51)	141	1.01 (24)	2.2

[a] Number of samples indicated in parentheses.
[b] Significantly greater than the upwind value ($p < 0.05$).

When on-plant TVP concentrations were compared with plant operating characteristics (such as wastewater throughput or air rate), or total viable wastewater concentrations, no obvious relationships were found. However, Sampling Locations 1–4 (Figure 1) were not always directly downwind. When the analysis is limited to those observations ± 22.5° from due east or west (Sites 2 and 4), a rough association ($r^2 = 0.46$) is evident (Figure 5). These concentrations reflect air passage across maximum tank surface areas. (The north–south distance is only 25% of that from east to west.) The spread in the data could not be further explained by systematic differences in wind speed, temperature, or relative humidity. Total coliform also did not show any striking relationships with wastewater concentrations or operating parameters.

Regression analysis did not find any linear relationships between TVP and total coliform concentrations and relative humidity, temperature, solar or ultraviolet radiation, day/night sampling, or wind direction. The plot of TVP versus wind speed at 0.8 km downwind of the plant (Figure 6) does show the characteristic negative sloping envelope found between other air pollutants and wind speed. No apparent trends were observed between either pollutant and relative humidity, temperature, or day/night sampling when the analysis was limited to days with similar windspeeds (within 8-km/h [5 = miles/hr] ranges).

NONVIABLE POLLUTANTS

Because particulate and gas measurements were 24-hour averages, the analyses of these data were somewhat different than for TVP and coliforms. As Table 3 indicates, 10 out of the 20 nonviable indices were below the detection limit on over half of the sampling days. Only 7 of the 20 indices were above the detection limit at one or more locations on every measurement day. When the mean concentrations were mapped, only the pattern for tin suggested a relationship to the plant (Figure 7). However, this pattern is based on only 18 measurements above the detection limit so that the identification of the plant as a source of tin is quite tentative. Enough data were collected for TSP, $SO_4^{=}$, NO_3^{-}, NO_2, SO_2, V, Mn, Cu, and Pb to warrant analysis by wind direction. A set of maps for TSP concentrations when winds were from the south, north, east, and west are shown in Figure 8. The major source of

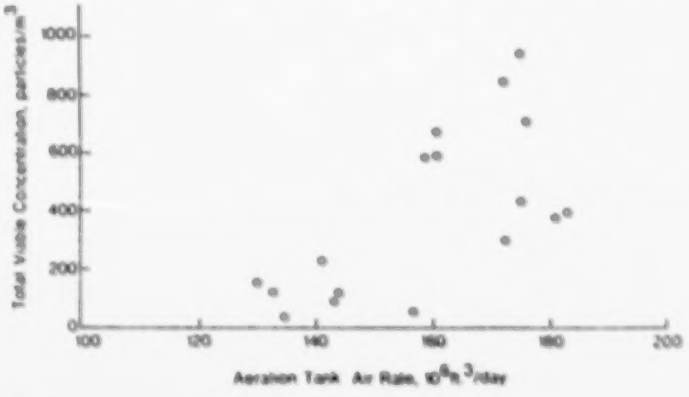

Figure 5—Total viable concentration versus aeration tank air rate.

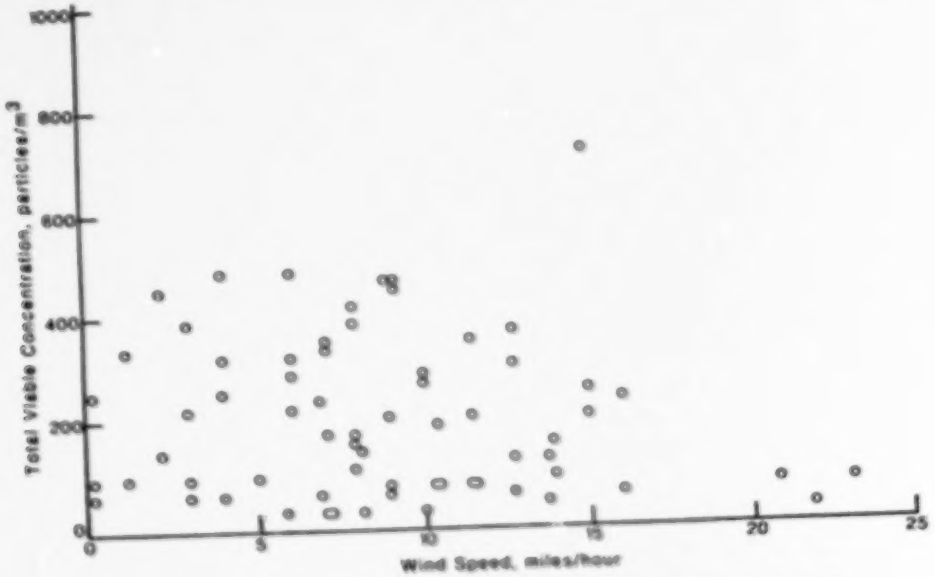

Figure 6—Total viable particle concentration 0.8 km downwind of the plant versus wind speed.

TSP was Chicago (south winds). East winds also resulted in relatively high concentrations, probably as a result of a major tunnel and reservoir construction project in the area. The wastewater treatment plant does not appear to be a major source. Patterns for the other eight particulate and gaseous pollutants by wind direction also did not identify the plant as a source. In addition, regression analysis did not find any linear relationships between plant operating or chemical parameters and nonviable pollutant concentrations. In general, the concentrations for all pollutants, with the possible exception of TSP and SO_x, were quite low for an urban setting, and even the levels of these two were not remarkable.

DISCUSSION

It is significant to note that the average concentrations of total viable and coliform particles measured during this study were much lower than have been previously reported in investigations of trickling filter plants.[3,6,9,10] For activated sludge plants, the total viable particle concentrations reported here were somewhat higher than those reported by Pereira and Benjamin-son;[7] comparable to those measured by Napolitano and Rowe[8] and Johnson *et al.*;[5] and much lower than those reported by Randall and Ledbetter.[11] The total coliform bacteria concentrations measured in this study using Andersen samplers can only be compared with one study that also used Andersen samplers at an activated sludge plant.[7] The results of that study are higher than those reported here, but distances of the samplers from the aeration tanks were not given. The lower values reported in this study probably result from the low velocity design of the air-addition pipes (10- to 30-μm porosity ceramic diffuser plates), to the unusually deep aeration tanks (4.2 to 4.6 m), and to the fact that no sludge treatment facilities are located at the plant. The implications of these conclusions for the emission and dispersion of other organisms, such as fecal coliform

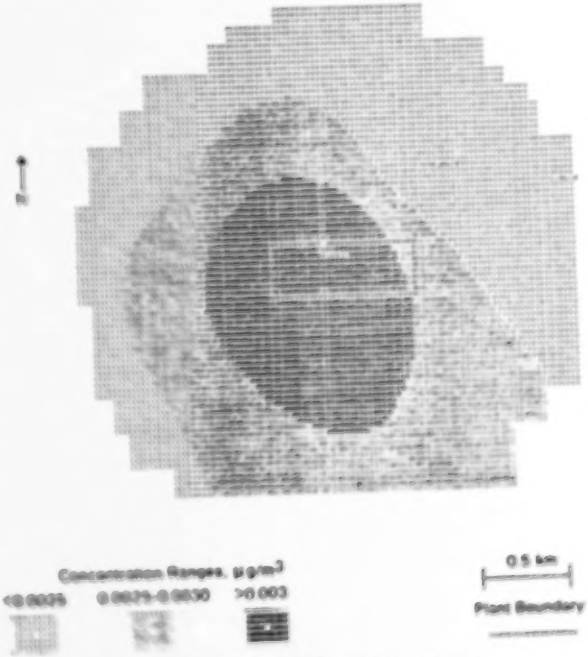

Figure 7—Concentration profile for airborne tin.

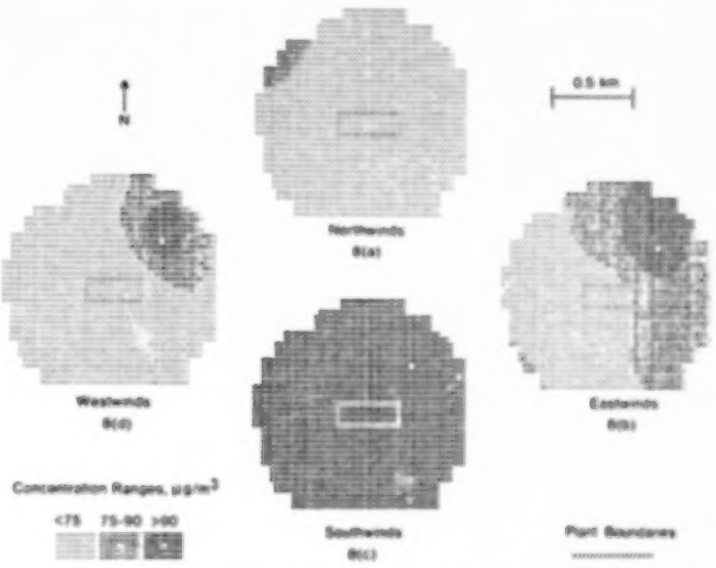

Figure 8—Total suspended particulate concentration profiles by wind direction: 8(a) north; 8(b) east; 8(c) south; 8(d) west.

and viruses, can not be completely determined at this time. Measurement of low concentrations of airborne organisms with even lower viability then coliforms presents a formidable experimental task.

The lack of correlation between viable measurements and meteorological variables is perhaps not unexpected. In general, it might be suggested that solar radiation, low relative humidities, low wind speeds, and high temperatures would give low viable particle recoveries. However, the available data appear to be somewhat equivocal in this regard. For instance, Goff, *et al.*[10] reported higher recoveries of both total bacteria and coliform at night than during the day. However, this effect may have been due to higher nighttime relative humidities. King *et al.*[4] reported increased recoveries with higher temperatures. Kenline and Scarpino[3] did not observe any trends with relative humidity or solar radiation, although their analysis possibly suggested better recoveries with higher humidities. Randall and Ledbetter[1] observed no variation in recovery with relative humidity or temperature but did report a rough positive relationship between the number of bacteria and the relative humidity when the wind speed factor was suppressed. Adams and Spendlove[9] suggested that solar radiation and humidity were important factors but did not present a systemized analysis of their data. Fannin *et al.*[5] found a significant inverse correlation between coliform concentration and ambient air temperature but no relationship between coliform and relative humidity. Lee *et al.*[23] found no appreciable association between total viable bacteria concentrations and temperature or relative humidity. Conclusive interpretation of these studies is also difficult because of the different methodologies used to collect bacteriological aerosols.

Even though various trace elements were found in the wastewater (Table 5), most are apparently not discharged into the air in sufficient quantities to be notable. The same was true for nitrates and sulfates. The lack of correlation between operating parameters and any of the nonviable pollutants is somewhat puzzling, particularly in light of the fact that both wastewater throughput and air rate independently varied by almost a factor of 2. Apparently, the quantities of sulfates, nitrates, and trace elements that are aerolized do not measureably contribute to the existing background concentrations. It may be that the aeration tank surface area and air discharge velocity are more important factors for emission of pollutants to the atmosphere.

In any case, based on the measurements of this study, the wastewater treatment plant is a significant source of TVP and total coliforms. Atmospheric TVP concentrations were elevated above background out to 1.6 km. Levels for total coliforms were reduced to background at less than 0.8 km, probably reflecting the limited viability of these bacteria in air. On the average, 95% of the viable particles discharged from the plant were greater than 2.1 μm, and 99% of the total coliform particles were greater than 1.1 μm.

The health implications of these pollutants for populations living in the vicinity of the plant are not well defined.[11] But the fact that plant emissions have the potential for relatively widespread dispersion should

alert those concerned with the operation, planning, and design of activated sludge processes to incorporate the most effective control measures possible.

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